NASA TECHNICAL MEMORANDUM

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A COMPILATION OF CURRENT COMPUTER PROGRAMS FOR LOW-THRUST TRAJECTORY ANALYSIS

by Alfred C. Mascy

NASA Headquarters
Mission Analysis Division
Moffett Field, Calif.

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SUMMARY

This paper provides a catalogue of brief descriptions of current low-thrust trajectory and mass computation programs. All known sources were contacted, and questionnaires were sent to those who indicated that they possessed such codes. A total of 59 descriptions of computer programs pertinent to this discipline are compiled. They are capable of generating flyby and rendezvous trajectories with their associated mass computation. Included in the codes are those capable of variable thrust trajectory as well as constant thrust with coast trajectory calculations. No attempt is made to evaluate any computer code or in any way compare programs; rather, the descriptions of existing codes are presented. Further details concerning a particular program may be obtained from the organization shown on each description. Many programs are well documented, and all organizations are encouraged to use the services provided by the regional dissemination center, COSMIC, located at the University of Georgia and sponsored by the NASA Office of Technology Utilization.

INTRODUCTION

There is increasing interest in the application of advanced propulsion systems, such as electric rockets, to advanced missions having high velocity requirements. Better utilization of existing computer programs, or the development of new codes supplemented by experience with existing programs, is needed to define these requirements. This survey indicates that numerous low-thrust computer programs now exist, but many are not reported in the literature. The majority of these programs are worthwhile and can be of greater use if they are made known to the community of low-thrust analysts.

Thus, the purpose of this paper is to provide a catalogue of brief descriptions of current low-thrust trajectory computer programs. This paper does not attempt to evaluate any computer code or to compare one program with another. The descriptions of computer codes pertinent to low-thrust mission analysis serve only to introduce the respective programs in order to advance research in this area by the exchange of ideas, trajectory concepts, and mathematical methods already applied.

Gratitude is expressed to all organizations participating in this survey; they gave freely of their time and information to enhance the scope of this work.

SYMBOLS

a_o	initial acceleration
Isp	specific impulse of thruster
$\frac{T}{W}$	thrust-to-weight ratio
V_∞	hyperbolic excess speed
α	power-plant specific mass
η	efficiency of thrusters
μ_L	payload mass fraction
μ_p	propellant mass fraction
μ_W	power-plant mass fraction

COMPILATION OF PROGRAM DESCRIPTIONS

All organizations that might possess a low-thrust computer program capability were contacted. After an initial contact by telephone, questionnaires (see sample on page 7) were sent to the individuals who wished to participate in the survey. The data on each completed questionnaire were transferred to an information sheet that did not include the multiple choice or nonapplicable answers. Some questionnaires were only partially completed but were accompanied by the program documentation, which was transferred to the information sheet. It is hoped that this transfer was done as accurately as the programmer would have done it. Copies of the information were sent to all participants for their comments, corrections, and updating. The present publication reflects all changes.

A total of 59 descriptions of programs pertinent to low-thrust trajectory and mass computation are compiled (pp. 8-66). It is believed that these represent most of the codes in this discipline. These descriptions represent approximately 52 different programs; many have been modified and are described as slightly different codes by various users. Rather than screen a program that may have been modified for the user's needs, all low-thrust code descriptions submitted have been included in this compilation. However, some programs were not directly applicable to low-thrust trajectory analysis and have not been included in this survey.

There are about twice as many two-dimensional codes as there are three-dimensional codes. Most two-dimensional codes utilize a polar coordinate system, while most three-dimensional programs use a Cartesian system. Only two programs actually appear to account for more than the usual two bodies in a gravitational system. Most codes have been programmed in Fortran IV, although a few require a knowledge of machine language. Most codes do require initial guesses such as the Lagrange multipliers; however, a few programs generate the necessary starting values from an approximate solution, such as a circular arc trajectory or an iterated circle start solution. A few programs are applicable only to the planetocentric phase, and the others are flyby and rendezvous decks; most programs are capable of both operations. There is an almost total absence of round-trip trajectory codes. Approximately 15 percent of the codes include some estimate of the planetocentric phase, as well as the heliocentric phase.

Potential users who are interested in further information on the programs are advised to contact the respective company. Many programs are well documented, and all organizations are encouraged to submit them to COSMIC for inclusion in the library of available programs. COSMIC is one of the newest regional dissemination centers located at the University of Georgia and sponsored by the NASA Office of Technology Utilization. In general, its purpose is to acquire and disseminate information and software (card decks, tapes, etc.) on technical and scientific computer programs originated during NASA work. Once a program is accepted by COSMIC, the authoring organization no longer needs to prepare and transmit its program to potential users. Organizations are encouraged to use the dissemination service.

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LOW-THRUST TRAJECTORY AND MASS COMPUTATION PROGRAM

Company Organization :

Name of Program :

Authors/Contact :

Program Funded by : i.e., company, NASA contract, . . .

Description

(Please circle or add appropriate comment.)

Number of Dimensions : i.e., 1, 2, 3

Number of Bodies : i.e., 2, 3, . . .

Coordinate System : i.e., Cartesian, polar, . . .

Integration Technique : i.e., variable step, fixed step, . . .

Program Language : i.e., Fortran IV, II, . . .

Computer Now Used : i.e., IBM 7094, CDC 6600, Univac 1108, . . .

Trajectory Options : i.e., flyby, rendezvous, round trip, . . .

Specific Impulse : i.e., variable, constant, . . .

Power Options : i.e., constant, function of time, function of distance, . . .

Other Options : . . .

Input (briefly) : i.e., position and velocity, Julian dates, hyperbolic excess velocity, ISP, powerplant specific mass, α, . . .

Initial Guesses Required: i.e., Lagrange multipliers, T/W, . . .

Parameters Optimized : i.e., ISP, T/W_O, μ_W, V_∞, power level, $\int a^2\, dt$, coast time, thrust angle, . . .

Optimization Technique : i.e., gradient method, Newton-Raphson, . . .

Output (briefly) : i.e., time history, ISP, T/W, payload, $\int a^2\, dt$,. . .

Planetocentric Phase : not included in program, high-thrust capture and departure, low-thrust spiralling, . . .

Limitations of Program : i.e., travel angle, T/local g, . . .

Other Applications of Program ______________________________

Documentation of Program ______________________________

Availability to Other Users ______________________________

Other Comments ______________________________

Please Mail Completed Form to: Alfred C. Mascy
NASA Mission Analysis Division, OART
Mail Stop 202-8
Moffett field, California 94035

Company/Organization	:	Aerojet General, Space General Plant, El Monte, California
Name of Program	:	ORPERT
Authors/Contact	:	Dr. Leonard Pode/Wayne F. Brady
Program Funded by	:	Company

Description

Number of Dimensions	:	3
Number of Bodies	:	Up to 5 satellites and Earth, Sun and Moon currently
Coordinate System	:	Cartesian
Integration Technique	:	Fixed step
Program Language	:	Fortran IV
Computer Now Used	:	IBM 360/40
Trajectory Options	:	Currently written for Earth orbit
Specific Impulse	:	Constant
Input (briefly)	:	Position and velocity, Julian dates, time to start & stop thrust, direction of thrust WRT VEL vector, magnitude of thrust, weight flow rate
Output (briefly)	:	Time history
Limitations of Program	:	Eccentricity $\neq 0$
Other Applications	:	Will handle up to 5 satellites in Earth orbit; includes perturbations due to atmosphere, Earth harmonics, Moon & Sun
Documentation	:	A report is in rough draft.
Availability	:	Program not completed due to funding.
Other Comments	:	JPL ephemeris tape used. Conversion to another gravitational center would not be difficult. Program originally written to simulate deployment and separation history of several satellites in orbit.

Company/Organization	:	AFIT-SEE, W-Patterson AFB, Ohio 45433
Name of Program	:	Low-Thrust Solar Probe
Authors/Contact	:	Major Roger W. Johnson/Capt. H. T. Brock

<u>Description</u>

Number of Dimensions	:	2
Number of Bodies	:	2
Coordinate System	:	Polar
Integration Technique	:	Variable step
Program Language	:	Fortran IV
Computer Now Used	:	IBM 7094
Trajectory Options	:	Flyby
Power Options	:	Constant
Input (briefly)	:	Position and velocity
Initial Guesses Required	:	T/W
Parameters Optimized	:	$\int a^2\, dt$
Optimization Technique	:	Newton-Raphson
Output (briefly)	:	Time history
Planetocentric Phase	:	Not included in program
Limitations of Program	:	Travel angle
Other Applications	:	Available approximately June 1968
Documentation	:	Thesis form
Availability	:	Yes (listing)

Company/Organization	:	Analytical Mechanics Associates, Inc.
Name of Program	:	2-Body Trajectory Optimization Program
Authors/Contact	:	J. H. Campbell
Program Funded by	:	Sub-contract from Princeton

<u>Description</u>

Number of Dimensions	:	3
Number of Bodies	:	N
Coordinate System	:	Cartesian
Integration Technique	:	In mass ratio
Program Language	:	Fortran IV
Computer Now Used	:	IBM 360
Trajectory Options	:	Flyby, rendezvous
Specific Impulse	:	Constant
Power Options	:	Constant, function of distance
Input (briefly)	:	Position and velocity, Julian dates, hyperbolic excess velocity, ISP, powerplant specific mass, alpha, launch vehicle, sizing parameters, etc.
Initial Guesses Required	:	Lagrange multipliers, T/W, and any unspecified initial conditions
Parameters Optimized	:	ISP, T/W_o, V_∞, coast time, thrust angle, t_o, t_f
Optimization Technique	:	Employs indirect method coupled with gradient method for solution of boundary value problem
Planetocentric Phase	:	High-thrust departure
Documentation	:	In progress
Availability	:	Available at Princeton U. and GSFC

Company/Organization	:	Analytical Mechanics Associates, Inc.
Name of Program	:	Second Variation Rocket Trajectory Optimization Program
Authors/Contact	:	Dr. Henry J. Kelley, Westbury, N. Y. Office
Program Funded by	:	Various NASA MSC contracts

Description

Number of Dimensions	:	3
Number of Bodies	:	2
Coordinate System	:	Cartesian
Integration Technique	:	Fixed step Runge-Kutta
Program Language	:	Fortran IV
Computer Now Used	:	IBM 360
Trajectory Options	:	Rendezvous and orbit transfer options
Specific Impulse	:	Constant
Power Options	:	Constant or solar
Input (briefly)	:	Initial and terminal conditions
Initial Guesses Required	:	First guess on steering history
Parameters Optimized	:	Steering histories and switch times
Optimization Technique	:	Second variation
Output (briefly)	:	Time history of control, state and multipliers
Planetocentric Phase	:	Not included
Limitations of Program	:	Program is primarily hight-thrust, but should handle low-thrust heliocentric well.
Documentation	:	Presently undocumented
Availability	:	Has been used exclusively in-house
Reference	:	"A Trajectory Optimization Technique Based Upon the Theory of the Second Variation," H. J. Kelly, R. E. Kopp and H. G. Moyer, AIAA No. 63-415, Aug. 19, 1963.

Company/Organization	:	AVCO
Name of Program	:	#1546 - Generalized Variation of Parameters Program
Authors/Contact	:	F. H. Scammell, M. Curley/D. P. Fields
Program Funded by	:	Company

Description

Number of Dimensions	:	3
Number of Bodies	:	N-Bodies (all planets, plus Sun and Moon)
Coordinate System	:	Cartesian
Integration Technique	:	Variable step (Adams 4th order predictor-corrector)
Program Language	:	Fortran IV
Computer Now Used	:	IBM 360/75, 360/65
Trajectory Options	:	Central body determination and switchover, flyby, round trip
Specific Impulse	:	Constant
Power Options	:	Constant
Other Options	:	Choice of perturbations including atmospheric retardation, perturbing planets, time-varying thrust orientation
Input (briefly)	:	Thrust level & orientation, perturbation controls, position and velocity, ISP, α
Initial Guesses Required	:	2-body initial conditions
Parameters Optimized	:	Not designed as optimization program
Output (briefly)	:	Variable format
Planetocentric Phase	:	High-thrust capture and departure, low-thrust spiralling
Other Applications	:	Guidance analysis
Documentation	:	AVCO Know-How Document (internal documentation)
Availability	:	Available for use on any funded study
Other Comments	:	A 2-body version (1546D) is available.

Company/Organization	:	Bell Telephone Laboratories
Name of Program	:	DEPAK; MULTI
Authors/Contact	:	A. J. Claus
Program Funded by	:	Company

Description

Number of Dimensions	:	3
Number of Bodies	:	3
Coordinate System	:	Cartesian
Integration Technique	:	Variable step
Program Language	:	Fortran IV
Computer Now Used	:	IBM 7094, GE 635
Specific Impulse	:	Variable, constant
Power Options	:	Constant, function of time, function of distance
Input (briefly)	:	Position and velocity, Julian dates, ISP
Output (briefly)	:	Time history
Documentation	:	Internal memoranda
Availability	:	Written request addressed to Bell Labs required
Other Comments	:	The program is essentially a general purpose numerical integration package with variable stepsize and operating in either single (8 digits) or double (16 digits) precision.

Company/Organization	:	The Boeing Co./Space Division - Guidance and Control
Name of Program	:	Variable Thrust Polynomial Optimizer
Authors/Contact	:	Forrester Johnson/Daril Hahn
Program Funded by	:	Company

Description

Number of Dimensions	:	3
Number of Bodies	:	2
Coordinate System	:	Cartesian
Integration Technique	:	Does not integrate
Program Language	:	Fortran IV
Computer Now Used	:	Univac 1108
Trajectory Options	:	Flyby, rendezvous
Specific Impulse	:	Variable
Power Options	:	Constant
Input (briefly)	:	Position and velocity, Julian dates, hyperbolic excess velocity, Isp
Initial Guesses Required	:	Self generating
Parameters Optimized	:	$\int a^2\, dt$
Optimization Technique	:	Newton-Raphson
Output (briefly)	:	Time history, a^2 dt
Planetocentric Phase	:	Not included in program
Availability	:	Decided on an individual basis
Other Comments	:	Uses an approximate, but rapid, method

Company/Organization	:	The Boeing Company/Space Div., Guidance and Control Organization
Name of Program	:	Space Trajectory Optimization Program (AS 2080)
Authors/Contact	:	D. W. Hahn, Berdein F. Itzen
Program Funded by	:	Company

<u>Description</u>

Number of Dimensions	:	3
Number of Bodies	:	2
Coordinate System	:	Polar
Integration Technique	:	Fixed step
Program Language	:	Fortran IV
Computer Now Used	:	Univac 1108
Trajectory Options	:	Flyby, rendezvous
Specific Impulse	:	Constant
Power Options	:	Constant, function of distance
Other Options	:	Planetocentric high-thrust departure to an input c_3
Input (briefly)	:	Position and velocity, Isp, V_∞
Initial Guesses Required	:	Control schedule
Parameters Optimized	:	Coast times, thrust angle, final mass
Optimization Technique	:	Gradient method
Output (briefly)	:	Time history, payload
Planetocentric Phase	:	High-thrust capture and departure; low-thrust spiralling
Other Applications	:	General orbit transfer maneuvers, any thrust level
Documentation	:	Documented except for recent revisions
Availability	:	Considered on an individual basis

Company/Organization	:	Colorado State University
Name of Program	:	Characteristic Length Method
Authors/Contact	:	Professor W. R. Mickelsen, Dept. of Mech. Eng.
Program Funded by	:	NASA Grant NGR06-002-032
		Description
Integration Technique	:	Program does not compute trajectory.
Program Language	:	Fortran IV
Computer Now Used	:	CDC 6400
Trajectory Options	:	Flyby, rendezvous, round trip, etc.
Specific Impulse	:	Variable, constant, other
Power Options	:	Constant, function of time, function of distance
Input (briefly)	:	Hyperbolic excess speed and transfer time from impulsive thrust trajectories, launch vehicle payload versus V_∞, α of total electric propulsion system, Isp, T/W_O
Initial Guesses Required	:	Propulsion time
Parameters Optimized	:	Isp, T/W_O, V_∞ (by inspection of output)
Output (briefly)	:	Approximate values of propulsion time, final mass of electric stage, final payload
Planetocentric Phase	:	High-thrust capture and departure
Limitations of Program	:	Trajectory similarity
Documentation	:	AIAA Paper No. 67-709
Availability	:	Upon request
Other Comments	:	The characteristic-length method is based on a nonrigorous assumption of similarity between low-thrust and impulsive-thrust trajectories. Although the output is only approximate, it may serve well as a fast source for first guess inputs to complex programs.
Reference	:	Zola, Charles L.: A Method of Approximating Propellant Requirements of Low-Thrust Trajectories. NASA TN D-3400, 1966.

Company/Organization	:	Computer Applications, Inc.
Authors/Contact	:	Moshe Mangad, Ph.D.

<u>Description</u>

Number of Dimensions	:	2, 3
Number of Bodies	:	2, 3, 4
Coordinate System	:	Cartesian, polar, nondimensional (i.e., Perkins Units)
Integration Technique	:	Variable and constant
Program Language	:	Fortran IV
Computer Now Used	:	IBM 7090/94, 704, Philco 5200
Trajectory Options	:	Flyby, rendezvous, moon transfer
Specific Impulse	:	Constant and variable
Power Options	:	Constant, function of time, distance
Other Options	:	Coast period as f(t, d), $\bar{f}(t)$, or f(d)
Input (briefly)	:	Position and velocity, vehicle/payload constraints
Initial Guesses Required	:	T/W
Parameters Optimized	:	Isp, V_∞, power level, T/W_o
Optimization Technique	:	Gradient method
Output (briefly)	:	Time history, Isp, T/W
Planetocentric Phase	:	Low thrust spiralling
Other Applications	:	Logistics study of Moon transfer
Other comments	:	4-body problem done for hyperbolic encounter study.

Company/Organization	:	University of Connecticut, Aerospace Engineering Dept.
Name of Program	:	PDER, PDERDP (double precision version)
Authors/Contact	:	Prof. Edward T. Pitkin
Program Funded by	:	N. Conn., Research Foundation

Description

Number of Dimensions	:	3
Number of Bodies	:	2
Coordinate System	:	Cartesian
Integration Technique	:	N/A
Program Language	:	Fortran IV
Computer Now Used	:	IBM 360/65
Trajectory Options	:	N/A
Input (briefly)	:	Position and velocity at EPOCH
Parameters Optimized	:	N/A
Other Applications	:	Computes transition matrix, inverse 2nd partials, perturbative derivatives, etc.
Availability	:	Single precision is share deck 3513; double precision version available from author.
Other comments	:	Program is a general solution of two-body motion for all orbit shapes with 1st and 2nd partial derivatives plus perturbative derivatives for use in a variation of parameters integration.

Company/Organization	:	General Dynamics/Convair
Name of Program	:	Convair Low-Thrust Optimization Programs
Authors/Contact	:	D. H. Higdon, J. F. Ingber, J. R. Grace
Program Funded by	:	Company

Description

Number of Dimensions	:	2, 3
Number of Bodies	:	2, N
Coordinate System	:	Cartesian
Integration Technique	:	Variable step, or fixed step
Program Language	:	Fortran IV
Computer Now Used	:	CDC 6400
Trajectory Options	:	Flyby, rendezvous, fixed time, free time
Specific Impulse	:	Variable or constant
Power Options	:	Constant
Other Options	:	Complete optimization from launch to capture (excluding spirals)
Initial Guesses Required	:	Lagrange multipliers
Parameters Optimized (only μ_W in traj. part)	:	Isp, T/W_O, μ_W, V_∞, power level, coast time, thrust angle, final payload weight
Optimization Technique	:	Newton-Raphson, maximum principle
Output (briefly)	:	Time history, Isp, T/W, payload
Planetocentric Phase	:	High-thrust capture and departure, low-thrust spiralling being developed
Documentation	:	Limited
Availability	:	Proprietary

Company/Organization	:	General Dynamics/Fort Worth Division
Name of Program	:	Y28 Optimum Low-Thrust Procedure
Authors/Contact	:	JPL/M. Poteet (Fort Worth Div.)
Program Funded by	:	Company

Description

Number of Dimensions	:	2, 3
Number of Bodies	:	2
Coordinate System	:	Polar
Integration Technique	:	Variable step
Program Language	:	Fortran IV
Computer Now Used	:	IBM 7094
Trajectory Options	:	Flyby, rendezvous
Specific Impulse	:	Variable, constant
Power Options	:	Constant, function of time
Input (briefly)	:	Position and velocity
Parameters Optimized	:	$\int a^2\, dt$
Optimization Technique	:	Newton-Raphson
Output (briefly)	:	$\int a^2\, dt$
Planetocentric Phase	:	Not included in program
Documentation	:	JPL Engineer Planning Document #179
Availability	:	Available from JPL
Other Comments	:	JPL program is on production status at Fort Worth Division.

Company/Organization	:	General Dynamics/Fort Worth Division
Name of Program	:	Low-Thrust Trajectory Optimization
Authors/Contact	:	D. H. Kruse
Program Funded by	:	Company

<u>Description</u>

Number of Dimensions	:	2, 3
Number of Bodies	:	2
Coordinate System	:	Cartesian, polar
Integration Technique	:	Fixed step
Program Language	:	Fortran IV
Computer Now Used	:	IBM 36-
Trajectory Options	:	Rendezvous
Specific Impulse	:	Constant
Power Options	:	Constant
Input (briefly)	:	Julian dates, Isp, α
Initial Guesses Required	:	Lagrange multipliers, flight time
Parameters Optimized	:	$\int a^2\, dt$, coast time, thrust angle
Optimization Technique	:	Newton-Raphson
Output (briefly)	:	$\int a^2\, dt$
Planetocentric Phase	:	Not included in program
Other Comments	:	Development of program is in initial phase.

Company/Organization	:	General Dynamics/Fort Worth Division
Name of Program	:	Interplanetary Low-Acceleration Constant-Thrust Trajectory Patching Program
Authors/Contact	:	S. W. Wilson/M. C. Poteet
Program Funded by	:	Company

<u>Description</u>

Number of Dimensions	:	2
Number of Bodies	:	2
Integration Technique	:	None
Program Language	:	Fortran IV
Computer Now Used	:	IBM 7090
Trajectory Options	:	Planetocentric
Specific Impulse	:	Constant
Power Options	:	Constant
Input (briefly)	:	Position, effective exhaust velocity, K_{planet}, initial acceleration
Initial Guesses Required	:	Initial (final) acceleration in heliocentric orbit
Parameters Optimized	:	None
Output (briefly)	:	$\int a^2\, dt$, "effective time to escape" (or capture), ΔV, mass ratio
Planetocentric Phase	:	Low-thrust spiralling
Limitations of Program	:	10^{-5} to 10^{-2} local "g" acceleration
Documentation	:	Customer Utilization Instructions, Procedure V06 (Co. document)
Availability	:	Proprietary, available under Government contract

Company/Organization	:	General Dynamics/Fort Worth Division
Name of Program	:	Low-Thrust Propulsion System Optimization Program
Authors/Contact	:	S. W. Wilson/M. C. Poteet (Fort Worth Div.)
Program Funded by	:	Company

Description

Number of Dimensions	:	2
Number of Bodies	:	2
Integration Technique	:	None
Program Language	:	Fortran IV
Computer Now Used	:	IBM 7090
Trajectory Options	:	One way heliocentric
Specific Impulse	:	Solved for in the program
Power Options	:	Constant
Input (briefly)	:	Powerplant specific mass α, avg. acceleration $\int a^2\,dt$, efficiency coefficients
Initial Guesses Required	:	None
Parameters Optimized	:	μ_W, μ_{final}, $a_{initial}$, c (exhaust velocity), η
Optimization Technique	:	Fibonaccian
Output (briefly)	:	max μ_λ, μ_W, μ_{final}, a_i, c, η
Planetocentric Phase	:	Not included in program
Documentation	:	Customer Utilization Instructions, Procedure V09 (Co. document)
Availability	:	Proprietary; available under Government contract

Company/Organization	:	General Electric Co. - Advanced Nuclear Systems Operation MSD
Name of Program	:	POLAR
Authors/Contact	:	Harold Brown
Program Funded by	:	Company

<u>Description</u>

Numbers of Dimensions	:	2
Number of Bodies	:	2
Coordinate System	:	Polar
Integration Technique	:	No integration used
Program Language	:	Fortran IV
Computer Now Used	:	IBM 7094
Trajectory Options	:	Flyby, rendezvous
Specific Impulse	:	Variable, constant
Power Options	:	Constant, function of time, function of distance
Other Options	:	See comment.
Input (briefly)	:	Position and velocity, Isp, α, V_∞
Parameters Optimized	:	T/W_O, power level, coast time, thrust angle
Optimization Technique	:	Gradient method
Output (briefly)	:	Time history, payload, T/W
Planetocentric Phase	:	Not included in program
Limitations of Program	:	See comment.
Documentation	:	Incomplete
Availability	:	Not recommended at this time
Other Comments	:	Program attempts to find a trajectory which will result in the specified power profile - constant or variable. Results to date have been unable to reduce deviations between the actual and specified power profiles to less than 10-15%.

Company/Organization	:	General Electric - Missile and Space Division
Name of Program	:	Finite Burn Orbit Insertion Program
Authors/Contact	:	D. Korenstein
Program Funded by	:	Company, NASA Contract

Description

Number of Dimensions	:	3
Number of Bodies	:	2
Coordinate System	:	Cartesian
Integration Technique	:	Fixed step
Program Language	:	Fortran IV
Computer Now Used	:	IBM 7094
Trajectory Options	:	Flyby, orbit insertion, escape
Specific Impulse	:	Constant
Other Options	:	2-point boundary value problem for orbit insertion
Input (briefly)	:	Hyperbola, ellipse, engine, guidance, planet
Parameters Optimized	:	T/W_o
Optimization Technique	:	Newton-Raphson
Output (briefly)	:	Gravity loss
Planetocentric Phase	:	High-thrust capture and departure, low-thrust spiralling
Other Applications	:	Open-loop low-thrust trajectories
Documentation	:	Not available
Availability	:	Yes
Other Comments	:	Program is partially checked out (in process)

Company/Organization	:	NASA Goddard Space Flight Center
Name of Program	:	Variable Power, Variable Thrust Option/F369
Contact	:	Kenneth I. Duck, Aux. Prop. Br.
Program Funded by	:	NAS 2-2928

<u>Description</u>

Number of Dimensions	:	3
Number of Bodies	:	2
Coordinate System	:	Cartesian
Integration Technique	:	Fixed step
Program Language	:	Fortran IV
Computer Now Used	:	IBM 7094
Trajectory Options	:	Flyby, rendezvous
Specific Impulse	:	Variable
Power Options	:	Constant, function of distance, function of time
Input (briefly)	:	Julian dates, hyperbolic excess velocity, powerplant specific mass, initial power
Parameters Optimized	:	$\int a^2 \, dt$
Optimization Technique	:	Newton-Raphson
Output (briefly)	:	Time history, $\int a^2 \, dt$
Planetocentric Phase	:	Not included in program

Company/Organization	:	Goddard Space Flight Center, Mission and Trajectory Analysis Division
Name of Program	:	Low-Thrust Trajectory Sub-Program
Contact	:	Robert T. Groves
Program Funded by	:	NASA Contract NAS 5-10029

Description

Number of Dimensions	:	2 or 3
Number of Bodies	:	2
Coordinate System	:	Cartesian
Integration Technique	:	Fixed step
Program Language	:	Fortran IV
Computer Now Used	:	IBM 7094
Trajectory Options	:	Rendezvous
Specific Impulse	:	Variable
Power Options	:	Constant
Input (briefly)	:	Position and velocity, hyperbolic excess velocity
Initial Guesses Required	:	Program uses ballistic trajectory for first fit
Parameters Optimized	:	$\int a^2\, dt$, thrust angle
Optimization Technique	:	Newton-Raphson
Output (briefly)	:	Time history of thrust acceleration and position, $\int a^2\, dt$
Documentation	:	In progress
Availability	:	Program still under development

Company/Organization	:	Grumman Aircraft, Bethpage, New York
Name of Program	:	Low-Thrust Interplanetary Trajectory Optimization
Authors/Contact	:	Hans K. Hinz and H. Gardner Moyer
Program Funded by	:	NASA-MSFC, Contract No. NAS 8-1549

<u>Description</u>

Number of Dimensions	:	3
Number of Bodies	:	2
Coordinate System	:	Cartesian
Integration Technique	:	Fixed step
Program Language	:	Fortran IV
Computer Now Used	:	IBM 360/75
Trajectory Options	:	Flyby, rendezvous
Specific Impulse	:	Constant
Other Options	:	Thrust constant, thrust variable but limited
Input (briefly)	:	Position and velocity and orbital elements of target planet
Initial Guesses Required	:	Control function(s)
Parameters Optimized	:	Thrust angles and thrust magnitude
Optimization Technique	:	Gradient method
Output (briefly)	:	Time history
Planetocentric Phase	:	Not included in program
Other Applications	:	See Grumman report, RE-208, April 1965
Documentation	:	See final report of Contract NAS 8-1549
Availability	:	Nonproprietary availability to interested users
Other Comments	:	RE-208 discusses GEOCENTRIC MISSIONS AND USE OF MORE EFFICIENT GENERALIZED NEWTON-RAPHSON METHOD OF OPTIMIZATION.

Company/Organization	:	Hayes International Corp.
Name of Program	:	Orbital Elements for Low Thrust Trajectories
Authors/Contact	:	Harry Passmore
Program Funded by	:	NASA Contract

Description

Number of Dimensions	:	3
Number of Bodies	:	2
Coordinate System	:	Orbital element
Integration Technique	:	Fixed step
Program Language	:	Fortran IV
Computer Now Used	:	1620 in part
Trajectory Options	:	Near Earth spiral
Specific Impulse	:	Constant
Other Options	:	Constant thrust
Input (briefly)	:	Position and velocity
Initial Guesses Required	:	Lagrange multipliers
Parameters Optimized	:	Thrust angle
Optimization Technique	:	Calculus of variations
Output (briefly)	:	Time history
Planetocentric Phase	:	Low-thrust spiralling
Documentation	:	NASA Report MTP-AERO-63-12
Other Comments	:	Not presently operable

Company/Organization	:	Hayes International Corp.
Name of Program	:	Quasi-Steady Orbital Rendezvous
Authors/Contact	:	Harry Passmore
Program Funded by	:	NASA Contract

Description

Number of Dimensions	:	2
Number of Bodies	:	Gravity of central body only
Coordinate System	:	Cartesian
Integration Technique	:	Fixed step
Program Language	:	Fortran IV
Computer Now Used	:	IBM 360
Trajectory Options	:	Transfer
Specific Impulse	:	Constant
Other Options	:	Thrust magnitude constant
Input (briefly)	:	Position and velocity, target position & velocity
Initial Guesses Required	:	None
Parameters Optimized	:	Thrust angle
Optimization Technique	:	Maximum principle
Output (briefly)	:	Time history
Planetocentric Phase	:	Not included in program
Limitations of Program	:	Initial longitude between vehicle & target <90°
Documentation	:	Hayes Engineering Report 1324
Availability	:	Computer program not published
Other Comments	:	Only used to date for circular orbit rendezvous

Company/Organization	:	Hughes Aircraft Company
Name of Program	:	Low-Thrust Trajectory
Authors/Contact	:	D. MacPherson or J. H. Molitor
Program Funded by	:	Partially Supported Under JPL Contract No. 951144

Description

Number of Dimensions	:	3
Number of Bodies	:	N
Coordinate System	:	Output in radius, ecliptic longitude, and normal to ecliptic
Integration Technique	:	Variable step or fixed step
Program Language	:	Fortran IV
Computer Now Used	:	GE 635
Trajectory Options	:	Flyby; rendezvous; round trip can be simulated by inputting cases sequentially.
Specific Impulse	:	Constant
Power Options	:	Function of time and/or function of distance
Other Options	:	Program converges automatically to a trajectory which satisfies terminal conditions; optimization is by parameter search.
Input (briefly)	:	Isp, powerplant specific mass, thrust profile, spacecraft mass, power profile, V_∞, launch date
Parameters Optimized	:	Program converges automatically to a trajectory which satisfies terminal conditions.
Optimization Technique	:	Parameter search
Output (briefly)	:	Time history
Planetocentric Phase	:	High-thrust capture, and departure
Documentation	:	Not complete
Availability	:	Subject to negotiation

Company/Organization	:	IBM Federal Systems Division
Name of Program	:	OPGUIDE
Authors/Contact	:	G. W. Johnson, 1730 Cambridge Street Cambridge, Mass.
Program Funded by	:	NASA Contract

Description

Number of Dimensions	:	3
Number of Bodies	:	2
Coordinate System	:	Cartesian
Integration Technique	:	Variable step
Program Language	:	Fortran IV
Computer Now Used	:	IBM 7094 - IBM System 360
Trajectory Options	:	Rendezvous
Specific Impulse	:	Variable
Power Options	:	Function of time
Input (briefly)	:	Position and velocity, Isp
Initial Guesses Required	:	Lagrange multipliers
Parameters Optimized	:	Coast time, thrust angle
Optimization Technique	:	Newton-Raphson
Output (briefly)	:	Time history
Other Applications	:	High thrust orbital transfers
Documentation	:	Preliminary
Availability	:	Limited

Company/Organization	:	IIT Research Institute
Name of Program	:	LTNAV-1 (Low-Thrust Navigation Analysis)
Authors/Contact	:	Alan L. Friedlander
Program Funded by	:	NASA Contract 2-22401 and 2-3348

Description

Number of Dimensions	:	3
Number of Bodies	:	2
Coordinate System	:	Cartesian, polar
Integration Technique	:	Variable step, fixed step
Program Language	:	Fortran II
Computer Now Used	:	IBM 7094
Trajectory Options	:	Flyby, rendezvous
Specific Impulse	:	Variable, constant
Power Options	:	Constant
Input (briefly)	:	Position and velocity
Initial Guesses Required	:	Lagrange multipliers for converged optimal trajectory
Parameters Optimized	:	Thrust angle
Optimization Technique	:	Calculus of variations
Output (briefly)	:	Time history
Other Applications	:	Navigation studies
Documentation	:	NASA CR-457

Company/Organization	:	IIT Research Institute
Name of Program	:	LTNAV-2 (Low-Thrust Planetocentric Navigation Analysis)
Authors/Contact	:	ALAN L. Friedlander
Program Funded by	:	NASA Contract 2-2401 and 2-3348

<u>Description</u>

Number of Dimensions	:	3
Number of Bodies	:	3
Coordinate System	:	Cartesian
Integration Technique	:	Variable step, fixed step
Program Language	:	Fortran IV
Computer Now Used	:	IBM 7094
Trajectory Options	:	Planetocentric only
Specific Impulse	:	Constant
Power Options	:	Constant
Other Options	:	Constant acceleration
Input (briefly)	:	Position and velocity, orbit elements
Output (briefly)	:	Time history
Planetocentric Phase	:	Program treats planetocentric phase only
Limitations of Program	:	Tangential thrust only
Documentation	:	NASA CR 740
Availability	:	Yes, but documentation is negligible.

Company/Organization	:	JPL
Name of Program	:	Optimum Thrust Programs for Power Limited Propulsion Systems (1016000)
Authors/Contact	:	Carl Sauer
Program Funded by	:	NASA Contract

Description

Number of Dimensions	:	2, 3
Number of Bodies	:	2
Coordinate System	:	Polar
Integration Technique	:	Variable step, fixed step
Program Language	:	FAP
Computer Now Used	:	IBM 7094
Trajectory Options	:	Flyby, rendezvous, solar probe, out of ecliptic, maximum energy
Specific Impulse	:	Variable, constant
Power Options	:	Constant, function of distance
Input (briefly)	:	Position and velocity, Julian dates, hyperbolic excess velocity, Isp, power-plant specific mass, α
Initial Guesses Required	:	Lagrange multipliers, T/W
Parameters Optimized	:	Isp, T/W_O, μ_W, V_∞, power level, $\int a^2\, dt$, coast time, thrust angle
Optimization Technique	:	Newton-Raphson
Output (briefly)	:	Time history, Isp, T/W, payload, $\int a^2\, dt$
Planetocentric Phase	:	High-thrust capture and departure, low-thrust spiralling; approximations made to heliocentric portion using "asymptotic velocity bias." Spirals and high thrust escape can be run separately.
Other Applications	:	Vehicle path optimization in vacuum
Documentation	:	JPL EPD 179 11/1/63, latest documentation lacking
Availability	:	Earlier version being used

Company/Organization	:	JPL
Name of Program	:	ASTRAL
Authors/Contact	:	D. Alderson/W. Stavro
Program Funded by	:	NASA Contract

Description

Number of Dimensions	:	3 (limited 3rd dimension)
Number of Bodies	:	2
Coordinate System	:	Spherical
Integration Technique	:	Analytic approximation
Program Language	:	Fortran IV
Computer Now Used	:	IBM 7094
Trajectory Options	:	Flyby, rendezvous
Specific Impulse	:	Constant
Power Options	:	Function of distance
Input (briefly)	:	Julian dates, Isp, powerplant specific mass, planet (target, launch), powerplant efficiency
Parameters Optimized	:	Isp, T/W_0, μ_W, V_∞, coast time, thrust angle
Optimization Technique	:	"Complex" method
Output (briefly)	:	Time history, Isp, T/W, payload
Planetocentric Phase	:	High-thrust capture and departure
Limitations of Program	:	Travel angle, T/local g, eccentricity of orbit
Initial Guesses Required	:	None
Availability	:	Not at present

Company/Organization	:	JPL
Name of Program	:	MALTS
Authors/Contact	:	TRW Systems/J. Driver
Program Funded by	:	NASA Contract NAS 7-503

<u>Description</u>

Number of Dimensions	:	3
Number of Bodies	:	Up to 10
Coordinate System	:	Spherical
Integration Technique	:	Cowell or Adams Moulton
Program Language	:	Fortran IV
Computer Now Used	:	IBM 7094
Trajectory Options	:	Flyby, rendezvous
Specific Impulse	:	Constant
Power Options	:	Function of distance
Input (briefly)	:	Position and velocity, Julian dates, excess velocity, Isp, powerplant specific mass, thrustor efficiency, time of flight
Initial Guesses Required	:	Lagrange multipliers, or orbit plane
Parameters Optimized	:	$\int a^2\, dt$, time, final mass, payload
Optimization Technique	:	Calculus of variations
Output (briefly)	:	Time history, $\int a^2\, dt$
Documentation	:	User's Manual available

Company/Organization	:	NASA Langley Research Center
Name of Program	:	PRESTO (DELTA)
Authors/Contact	:	Robert E. Smith
Program Funded by	:	NASA Contract

Description

Number of Dimensions	:	3
Number of Bodies	:	2
Coordinate System	:	Polar
Integration Technique	:	Fixed step
Program Language	:	Fortran IV
Computer Now Used	:	CDC 6600
Trajectory Options	:	Rendezvous
Specific Impulse	:	Constant
Power Options	:	Constant
Other Options	:	Earth to orbit transfer, Earth to Lunar transfer
Input (briefly)	:	Position and velocity
Initial Guesses Required	:	Control history, coast angle
Parameters Optimized	:	Coast time, thrust angle
Optimization Technique	:	Gradient method
Output (briefly)	:	Time history
Planetocentric Phase	:	Not included in program
Other Applications	:	Earth orbit missions, Lunar missions
Documentation	:	NASA CR-158
Availability	:	See note below.
Other Comments	:	Program applicable for preliminary studies

NOTE: The Presto Program is available from the COSMIC Computer Center, University of Georgia, Athens, Georgia, 30601. Their identification number for the program is LAR-10078.

Company/Organization	:	NASA Langley Research Center
Name of Program	:	TOMSD (Trajectory Optimization by Method of Steepest Descent)
Authors/Contact	:	Robert E. Smith
Program Funded by	:	Air Force-NASA contract

Description

Number of Dimensions	:	3
Number of Bodies	:	1 or more
Coordinate System	:	Rectangular
Integration Technique	:	Variable or fixed step
Program Language	:	Fortran IV
Computer Now Used	:	CDC 6000
Trajectory Options	:	Reentry, boost, rendezvous
Input (briefly)	:	Position and velocity
Initial Guesses Required	:	Control history
Parameters Optimized	:	Angle of attack, bank angle, initial state
Optimization Technique	:	Gradient method
Output (briefly)	:	Time history
Planetocentric Phase	:	Not included in program
Documentation	:	Technial Report AFFDL-TR-67-108, Vols. I, II, III
Availability	:	Upon request
Other Comments	:	This program is applicable to a variety of trajectory optimization problems.

Company/Organization	: NASA Lewis Research Center
Name of Program	: Lewis N-Body Code
Authors/Contact	: William C. Strack
Program Funded by	: Company

<u>Description</u>

Number of Dimensions	: 2, 3
Number of Bodies	: 2, 3, 8
Coordinate System	: Cartesian, orbit elements
Integration Technique	: Variable step, fixed step
Program Language	: Fortran IV
Computer Now Used	: IBM 7094, CDC 6600, IBM 7044
Trajectory Options	: Flyby, rendezvous
Specific Impulse	: Constant
Power Options	: Constant, function of distance
Other Options	: Targeting iteration, choice of thrust control
Input (briefly)	: Position and velocity, Julian dates, Isp, α, V_∞, tank and structure fraction
Initial Guesses Required	: Lagrange multipliers, T/W, thrust angle ♃, $\dot{♃}$, etc.
Parameters Optimized	: Isp, T/W_O, V_∞, power level, coast time, thrust angle
Optimization Technique	: Calculus of variations, univariate search
Output (briefly)	: Time history, payload
Planetocentric Phase	: High-thrust capture and departure, low-thrust spiralling
Other Applications	: Booster ascent paths
Documentation	: TN D-1730 with supplementary material
Availability	: Yes: 25 copies already sent out.
Other Comments	: Several versions of code exist (see NASA TM X52322).

LOW-THRUST TRAJECTORY AND MASS COMPUTATION PROGRAM

Company Organization	:	NASA-Lewis Research Center
Name of Program	:	MAXIM
Authors/Contact	:	E. A. Willis, Jr.
Program Funded by	:	Lewis Research Center (in-house)

Description

Number of Dimensions	:	2
Number of Bodies	:	2
Coordinate System	:	Polar
Integration Technique	:	Runge-Kutta with variable step size and error control
Program Language	:	Fortran IV
Computer Now Used	:	IBM 7094
Trajectory Options	:	Orbit escape, capture, or transfer
Specific Impulse	:	Constant I_{sp}
Power Options	:	Constant power implied
Other Options	:	Constant thrust, constant acceleration
Input	:	Position and velocity; vehicle design parameters for each stage (up to 5)
Initial Guesses Required	:	Initial positions and one multiplier (λ_θ)
Parameters Optimized	:	Thrust steering and switching program, staging points and acceleration levels are optimized for minimum ΔV or weight
Optimization Technique	:	Maximum principle with conjugate-gradient search for the 2-point b.v.p.'s
Output	:	Time history, ΔV's, weights
Documentation of Program	:	Theory and typical application covered in TN D-3606, TN D-4534, and TN D-5011.
Availability to Other Users	:	Considered individually. Operating instructions are in the form of internal notes only.

Company/Organization	:	Research Laboratories; Lockheed Missiles and Space Company
Name of Program	:	Low-Thrust Heliocentric Transfers
Authors/Contact	:	H. E. Rauch
Program Funded by	:	Company

Description

Number of Dimensions	:	2 or 3
Number of Bodies	:	Vehicle plus up to three planets
Coordinate System	:	Cartesian
Integration Technique	:	Fixed step
Program Language	:	Fortran IV
Computer Now Used	:	Univac 1108
Trajectory Options	:	Flyby, rendezvous, and round trip with variable acceleration only, rendezvous with constant acceleration
Specific Impulse	:	Variable, constant
Power Options	:	Constant
Input (briefly)	:	Position and velocity of planets, elapsed time
Initial Guesses Required	:	Lagrange multipliers
Parameters Optimized	:	$\int a^2\, dt$, coast time, thrust angle for constant acceleration
Optimization Technique	:	Guessing adjoint variables
Output (briefly)	:	Time history, $\int a^2\, dt$
Planetocentric Phase	:	Not included in program
Limitations of Program	:	Not "production" type program
Documentation	:	"Low Thrust Swingby Trajectories," by H. E. Rauch, XVIIIth International Astronautical Congress - Belgrade, 1967, Pergamon Press, Oxford, New York, PWN-Polish Scientific Publishers, 1968, pp. 269-284.
Availability	:	Could be made available

Company/Organization	:	Research Laboratories, Lockheed Missiles and Space Co.
Name of Program	:	Low-Thrust Escape From Planet
Authors/Contact	:	H. E. Rauch
Program Funded by	:	Company

<u>Description</u>

Number of Dimensions	:	2
Number of Bodies	:	2
Coordinate System	:	Both, but primarily polar
Integration Technique	:	Variable step
Program Language	:	Fortran IV
Computer Now Used	:	Univac 1108
Specific Impulse	:	Variable, constant acceleration
Power Options	:	None, trajectory with constant acceleration in velocity direction
Input (briefly)	:	Initial position and velocity, final desired hyperbolic excess velocity, constant or "average" acceleration
Initial Guesses Required	:	Lagrange multipliers
Parameters Optimized	:	$\int a^2\,dt$, thrust angle for constant acceleration
Optimization Technique	:	Guessing adjoint variables
Output (briefly)	:	Time history, $\int a^2\,dt$
Planetocentric Phase	:	Low-Thrust spiralling
Limitations of Program	:	Not "production" type program
Other Applications	:	Uses asymptotic matching to calculate heliocentric "offsets"
Documentation	:	"Optimum Guidance for a Low Thrust Interplanetary Vehicle," J. Breakwell and H. Rauch, AIAA Journal, Vol. 4, No. 4, April 1966
Availability	:	Could be made available

Company/Organization	:	Lockheed Missiles & Space Co./Advanced Flight Mechanics
Name of Program	:	LTCØMP
Authors/Contact	:	M. A. Krop, Dept. 55-34, B. 201, Ext. 45869
Program Funded by	:	Company

Description

Number of Dimensions	:	2, 3
Number of Bodies	:	4
Coordinate System	:	Planet-center & aligned along the excess velocity vectors
Integration Technique	:	None
Program Language	:	Fortran IV
Computer Now Used	:	Univac 1108
Trajectory Options	:	Single-leg interplanetary transfer
Specific Impulse	:	Variable, constant
Power Options	:	Constant
Input (briefly)	:	Julian dates, planet numbers
Initial Guesses Required	:	Time offsets at terminal planets
Parameters Optimized	:	$\int a^2\,dt$
Optimization Technique	:	Analytic approximation
Output (briefly)	:	$\int a^2\,dt$
Planetocentric Phase	:	Not included in program
Limitations of Program	:	Travel angle
Documentation	:	Method described in Chapter 4 of LMSC Rept. No. 3-17-64-1, Apr. 30, 1964
Availability	:	Still being developed
Other Comments	:	LTCØMP rapidly simulates the propulsion requirements for a low-thrust transfer. Although quite simplified, it computes optimum $\int a^2\,dt$ to within a couple of percent of rigorously optimized values.

Company/Organization	:	Los Alamos Scientific Laboratory, Los Alamos, New Mexico
Name of Program	:	1965 Version, produced by Dept. of Aerospace and Mechanical Sciences, Princeton Univ., Report No. 7170-1
Program Funded by	:	AEC

Description

Number of Dimensions	:	2
Number of Bodies	:	2
Coordinate System	:	Polar
Integration Technique	:	Variable step
Program Language	:	Fortran IV
Computer Now Used	:	IBM 7094, IBM 7030
Trajectory Options	:	Rendezvous
Specific Impulse	:	Constant
Power Options	:	Constant (with coast)
Input (briefly)	:	Position and velocity, Isp
Initial Guesses Required	:	Lagrange multipliers
Parameters Optimized	:	Coast time, thrust angle
Optimization Technique	:	Direct
Output (briefly)	:	Time history, T/W
Planetocentric Phase	:	Not included in program

Company/Organization	:	McDonnell Douglas Astronautics Company
Name of Program	:	FYNDIF
Authors/Contact	:	F. I. Mann
Program Funded by	:	Company

<u>Description</u>

Number of Dimensions	:	2
Number of Bodies	:	2
Coordinate System	:	Cartesian
Integration Technique	:	Second order finite difference procedure
Program Language	:	Fortran IV
Computer Now Used	:	Univac 1108
Trajectory Options	:	Rendezvous, intercept
Input (briefly)	:	Position and velocity, hyperbolic excess velocity
Parameters Optimized	:	$\int a^2 \, dt$
Optimization Technique	:	Calculus of variations and Van Dine's Generalized Newton-Raphson
Output (briefly)	:	Time history
Planetocentric Phase	:	Not included in program
Limitations of Program	:	Experimental program, planets in circular orbits, few options

Company/Organization	:	McDonnell Douglas Astronautics Company
Name of Program	:	LOWTOP, High-Low Thrust Trajectory Optimization Program
Authors/Contact	:	Jerry L. Horsewood/F. I. Mann
Program Funded by	:	Company

Description

Number of Dimensions	:	2
Number of Bodies	:	2
Coordinate System	:	Cartesian
Integration Technique	:	Variable step, fourth-order Runge Kutta
Program Language	:	Fortran IV
Computer Now Used	:	Univac 1108
Trajectory Options	:	Flyby, rendezvous
Specific Impulse	:	Variable, constant
Power Options	:	Constant or variable
Input (briefly)	:	Position and velocity, Julian dates, V_∞, Isp, thrust, power, weight-flow
Initial Guesses Required	:	Lagrange multipliers
Parameters Optimized	:	$\int a^2\, dt$, coast time, thrust angle, flight time, final speed
Optimization Technique	:	Newton-Raphson, maximum principle
Output (briefly)	:	Time history, Isp, T/W, velocity loss
Planetocentric Phase	:	High-thrust capture and departure
Other Applications	:	See company documentation on LOWTOP
Documentation	:	First draft complete
Availability	:	Currently not available

Company/Organization	:	McDonnell Douglas Astronautics Company
Name of Program	:	WHAMO, Weight History and Mission Optimizer
Authors/Contact	:	F. I. Mann
Program funded by	:	Company

Description

Number of Dimensions	:	2
Number of Bodies	:	2
Coordinate System	:	Cartesian
Integration Technique	:	Variable step, Fourth-order Runge Kutta
Program Language	:	Fortran IV
Computer Now Used	:	Univac 1108
Trajectory Options	:	Rendezvous, round trip, multi-leg missions
Specific Impulse	:	Variable or constant
Power Options	:	Variable or constant
Input (briefly)	:	Julian dates, hyperbolic excess velocity, Isp, thrust, power, weight flow
Initial Guesses Required	:	Lagrange multipliers, T/W
Parameters Optimized	:	Isp, coast time, thrust angle, gross weight
Optimization Technique	:	Newton-Raphson
Output (briefly)	:	Time history, Isp, T/W
Planetocentric Phase	:	High capture and departure with engine shutdown & restart
Other Applications	:	Simulates both high and low thrust engine shutdown and restart with high thrust staging according to the non-integral-burn method
Documentation	:	Partial
Availability	:	Currently not available
Other Comments	:	Program not extensively used yet

Company/Organization	:	McDonnell Douglas Astronautics Company
Name of Program	:	HITOP
Authors/Contact	:	F. I. Mann
Program Funded by	:	Company

<u>Description</u>

Number of Dimensions	:	3
Number of Bodies	:	2
Coordinate System	:	Cartesian
Integration Technique	:	Impulse trajectories analytic solution
Program Language	:	Fortran IV
Computer Now Used	:	Univac 1108
Trajectory Options	:	Rendezvous
Input (briefly)	:	Julian dates
Initial Guesses Required:	:	Time and place of deep space impulse
Parameters Optimized	:	Either $(V_{\infty 1} + \Delta V_2 + V_{\infty 3})$ or $(\Delta V_1 + \Delta V_2 + \Delta V_3)$
Optimization Technique	:	Newton-Raphson or transversality procedure
Output (briefly)	:	Primer vector, V_∞, ΔV, orbit parameters
Planetocentric Phase	:	High-thrust capture and departure
Limitations of Program	:	Currently only one deep-space impulse
Other Applications	:	Program may be used to study the high-thrust limit of low-thrust trajectories.
Documentation	:	None
Availability	:	Currently not available

Company/Organization	:	Space Division, North American Rockwell Corp.
Name of Program	:	Optimum Trajectory Program for Power-Limited Propulsion Systems
Authors/Contact	:	Russell P. Nagorski
Program Funded by	:	Company

Description

Number of Dimensions	:	3
Number of Bodies	:	4
Coordinate System	:	Polar
Integration Technique	:	Fixed step
Program Language:	:I	II
Computer Now Used	:	IBM 7094
Trajectory Options	:	Flyby, rendezvous
Specific Impulse	:	Variable, constant
Power Options	:	Constant
Input (briefly)	:	Position and velocity, Julian dates, V_∞, Isp, α
Initial Guesses Required	:	Lagrange multipliers, T/W
Parameters Optimized	:	$\int a^2\, dt$, coast time
Optimization Technique	:	Newton-Raphson
Output (briefly)	:	Time history, Isp, T/W, payload, $\int a^2\, dt$
Planetocentric Phase	:	Not included in program
Limitations of Program	:	Initial guess, iteration logic
Other Applications	:	General intercept and rendezvous problems
Documentation	:	User's Manual complete
Other Comments	:	Derivative of JPL (Melbourne and Sauer) program

Company/Organization	:	Mission Analysis Division, OART/NASA
Name of Program	:	BABE
Authors/Contact	:	A. C. Mascy/S. W. Pitts
Program Funded by	:	In-house

Description

Number of Dimensions	:	2
Number of Bodies	:	2
Coordinate System	:	Polar
Integration Technique	:	Variable step and fixed step
Program Language	:	Fortran IV
Computer Now Used	:	IBM 7094
Trajectory Options	:	Flyby, rendezvous
Specific Impulse	:	Constant
Power Options	:	Constant
Input (briefly)	:	Julian dates, hyperbolic excess velocity, α
Parameters Optimized	:	Isp, μ_W, coast time
Optimization Technique	:	Gradient method
Output (briefly)	:	Coast time, Isp, payload, μ_W
Planetocentric Phase	:	High-thrust capture and departure, low-thrust spiralling
Documentation	:	In progress

Company/Organization	:	Mission Analysis Division, OART/NASA
Name of Program	:	QUICKLY
Authors/Contact	:	Alfred C. Mascy
Program Funded by	:	In-house

Description

Number of Dimensions Number of Bodies Coordinate System Integration Technique	Program uses functional relationships for the energy requirements of pre-computed built-in performance data which were obtained by accurate 3-dimensional, 2-body, Cartesian coordinate, Newton-Raphson finite-difference programs.

Program Language	:	Fortran IV
Computer Now Used	:	IBM 360/50
Trajectory Options	:	Flyby, rendezvous, solar probe, extra-ecliptic, comet intercept
Specific Impulse	:	Constant
Power Options	:	Constant, function of time or distance
Other Options	:	Optimum or fixed power level or alpha as a function of power. Also, optimum or fixed hyperbolic excess velocities
Input (briefly)	:	Trip time, power plant specific mass α, launch vehicle name, capture and departure mode
Initial Guesses Required	:	None
Parameters Optimized	:	Isp, μ_W, $V_{\infty 1}$, $V_{\infty 2}$, power level, coast time
Optimization Technique	:	Gradient method and Newton-Raphson
Output (briefly)	:	Payload, Isp, μ_W, $V_{\infty 1}$, $V_{\infty 2}$, power level, powered time, also, plot option
Planetocentric Phase	:	High-thrust capture and departure, low-thrust spiralling, launch vehicle boost
Other Applications	:	May be used to determine performance of two-impulse ballistic systems for comparisons
Documentation	:	In progress
Availability	:	Upon request

Company/Organization	:	ASMAR, Princeton University
Name of Program	:	Lion 1
Authors/Contact	:	J. Campbell/P. M. Lion
Program Funded by	:	NASA contract

Description

Number of Dimensions	:	3
Number of Bodies	:	2
Coordinate System	:	Cartesian
Integration Technique	:	Variable step
Program Language	:	Fortran IV
Computer Now Used	:	IBM 7094, CDC 6600, IBM 360/50
Trajectory Options	:	Flyby, rendezvous, round trip, escape*
Specific Impulse	:	Constant
Power Options	:	Constant, function of time, function of distance
Other Options	:	Booster selection
Input (briefly)	:	Position and velocity or Julian dates, power plant specific mass, tankage, structure factors
Initial Guesses Required	:	Lagrange multipliers
Parameters Optimized	:	Isp, T/W_o, μ_W, V_∞, power level, coast time, thrust angle*
Optimization Technique	:	Neighboring extremal
Output (briefly)	:	Time history, Isp, T/W, payload
Planetocentric Phase	:	High-thrust capture and departure
Other Applications	:	Iterator can be used to solve any nonlinear (algebraic) equations.
Documentation	:	In progress
Availability	:	Available on request
Other Comments	:	*Other options available depending on input

Company/Organization	:	ASMAR, Princeton University
Name of Program	:	Campbell 1 (Modified Item)
Authors/Contact	:	J. Campbell/P. M. Lion
Program Funded by	:	NASA contract

<u>Description</u>

Number cf Dimensions	:	3
Number of Bodies	:	9
Coordinate System	:	Cartesian
Integration Technique	:	Variable step
Program Language	:	Fortran IV
Computer Now Used	:	IBM 7094, IBM 360/50
Trajectory Options	:	Flyby, rendezvous
Specific Impulse	:	Constant
Power Options	:	Constant, function of time, function of distance
Other Options	:	Programmed thrust
Input (briefly)	:	Position and velocity or Julian dates
Initial Guesses Required	:	Lagrange multipliers
Optimization Technique	:	Neighboring extremal
Planetocentric Phase	:	Included in program
Other Applications	:	Uses generalized iterator
Documentation	:	Partially complete
Availability	:	Difficult to transfer
Other Comments	:	Used mainly as check on 2-body program

Company/Organization	:	ASMAR, Princeton University
Name of Program	:	Gordon 2
Authors/Contact	:	C. N. Gordon/P. M. Lion
Program Funded by	:	NASA contract

<u>Description</u>

Number of Dimensions	:	2
Number of Bodies	:	2
Coordinate System	:	Polar
Integration Technique	:	Fixed step
Program Language	:	Fortran IV
Computer Now Used	:	IBM 7094, CDC 6600 (now being adapted), IBM 360/50
Trajectory Options	:	Flyby, rendezvous, round trip, constrained velocity flyby
Specific Impulse	:	Constant
Power Options	:	Constant, function of time, function of distance
Other Options	:	Select booster
Input (briefly)	:	Position and velocity or Julian dates (can input or optimize: excess velocity, Isp), power plant specific mass, α, tankage, structure factors
Initial Guesses Required	:	Lagrange multipliers
Parameters Optimized	:	Isp, T/W_O, μ_W, V_∞, power level, direction of arrival velocity, coast time, thrust angle, C_3
Optimization Technique	:	Neighboring extremal
Output (briefly)	:	Time history, Isp, T/W, payload, summary
Planetocentric Phase	:	High-thrust capture and departure
Documentation	:	In progress
Availability	:	Available on request
Other Comments	:	Also being used at Battelle, IITRI, MSFC

Company/Organization	:	ASMAR, Princeton University
Name of Program	:	PRIMER
Authors/Contact	:	M. Minkoff/P. M. Lion
Program Funded by	:	NASA contract

<u>Description</u>

Number of Dimensions	:	3
Number of Bodies	:	2
Coordinate System	:	Cartesian
Integration Technique	:	Impulsive trajectories analytic solution
Program Language	:	Fortran IV
Computer Now Used	:	IBM 7094
Trajectory Options	:	Flyby, rendezvous
Input (briefly)	:	Position and velocity or Julian dates
Optimization Technique	:	Conjugate gradient
Output (briefly)	:	Time history, $J = \Sigma_i \lvert \Delta\vec{V}_i \rvert$
Planetocentric Phase	:	High-thrust capture and departure
Documentation	:	In thesis form
Availability	:	Available on request
Other Comments	:	Finds optimum impulsive trajectory regardless of the number of impulses

Company/Organization	: Rand Corp.
Name of Program	: ROCKET
Authors/Contact	: B. W. Boehm
Program Funded by	: USAF Project RAND

<u>Description</u>

Number of Dimensions	: 3
Number of Bodies	: 4
Coordinate System	: Cartesian, polar
Integration Technique	: Variable step, fixed step, Cowell method
Program Language	: Fortran IV, II
Computer Now Used	: IBM 7094, CDC 6600, Univac 1108, GE 635
Trajectory Options	: Flyby, departure and capture
Specific Impulse	: Variable, constant
Power Options	: Constant, function of time
Other Options	: Numerous propulsion, aerodynamic, guidance options
Input (briefly)	: Position and velocity
Output (briefly)	: Time history, Isp, T/W, osculating orbit parameters, tracking obs.
Planetocentric Phase	: High-thrust capture and departure, low-thrust spiralling
Limitations of Program	: Cowell method makes ROCKET inefficient for long-duration trajectories.
Other Applications	: Boost, reentry, airbreathing propulsion
Documentation	: Book: ROCKET, by B. W. Boehm, Prentice-Hall, 1964
Availability	: Through SHARE Distribution Agency, 112 E. Post Road, White Plains, New York (send blank mag. tape, ask for #3001 (Fortran II version) or #3485 (Fortran IV version))

Company/Organization	:	RCA/Astro Electronics Division
Name of Program	:	Gordon 2
Authors/Contact	:	C. N. Gordon/J. M. L. Holman
Program Funded by	:	Company, NASA contract

Description

Number of Dimensions	:	2
Number of Bodies	:	2
Coordinate System	:	Polar
Integration Technique	:	Fixed step
Program Language	:	Fortran IV
Computer Now Used	:	IBM 7094, IBM 360/50
Trajectory Options	:	Flyby, rendezvous
Specific Impulse	:	Constant
Power Options	:	Constant, function of time, function of distance
Other Options	:	Choice of launch vehicle, sweep of parameters
Input (briefly)	:	Julian dates, power plant specific mass
Initial Guesses Required	:	Lagrange multipliers, T/W, power, C_3
Parameters Optimized	:	Isp, T/W_o, V_∞, power level, coast time, thrust angle, C_3
Optimization Technique	:	Neighboring extremal
Output (briefly)	:	Time history, Isp, T/W, payload
Planetocentric Phase	:	High-thrust capture and departure
Documentation	:	In progress
Availability	:	Available through ASMAR, Princeton University

Company/Organization	:	System Sciences Corp. (Subsidiary of Computer Science Corp.)
Name of Program	:	High-Precision, Low-Thrust Integration and Optimization Prog.
Authors/Contact	:	Pitkin and Baker/Dr. R. M. L. Baker, Jr.
Program Funded by	:	Company

<u>Description</u>

Number of Dimensions	:	3
Number of Bodies	:	Any number for which ephemerides are given
Coordinate System	:	Cartesian
Integration Technique	:	Variable step
Program Language	:	II
Computer Now Used	:	IBM 7094
Trajectory Options	:	Open
Specific Impulse	:	Variable
Power Options	:	Function of time
Input (briefly)	:	Position and velocity, Isp
Initial Guesses Required	:	Lagrange multipliers
Parameters Optimized	:	Power level
Optimization Technique	:	Gradient method
Output (briefly)	:	Time history
Planetocentric Phase	:	Low-thrust spiralling
Other Applications	:	Can interface with other impulsive thrust programs
Documentation	:	Listing of basic program
Availability	:	Yes
Other Comments	:	Utilizes universal variable so that it can pass evenly from ellipses through parabolas, to hyperbolas

Company/Organization	:	U. of Texas, Austin, Dept. of Aerospace Eng.
Name of Program	:	NMS
Authors/Contact	:	G. J. Lastman & W. T. Fowler
Program Funded by	:	NASA contract and graduate student and faculty time contributions

Description

Number of Dimensions	:	3
Number of Bodies	:	2
Coordinate System	:	Cartesian
Integration Technique	:	Fixed step
Program Language	:	Fortran IV
Computer Now Used	:	CDC 6600
Trajectory Options	:	Rendezvous
Specific Impulse	:	Constant
Power Options	:	Constant
Input (briefly)	:	Position and velocity, or Julian dates
Initial Guesses Required	:	Lagrange multipliers
Parameters Optimized	:	$\int a^2\ dt$, flight time
Optimization Technique	:	Perturbation
Output (briefly)	:	Time history, initial multipliers
Planetocentric Phase	:	Not inluded in program, capture being implemented
Limitations of Program	:	Travel time limit of $\approx$ 1000 days
Documentation	:	Limited
Availability	:	Listing and/or deck on request

Company/Organization	:	TRW Systems/Analytic Mechanics Dept.
Name of Program	:	MALTS, Mission Analysis & Simulation Program
Authors/Contact	:	D. B. Smith & W. D. Dickerson (R3/T, 3442)
Program Funded by	:	NASA contract

Description

Number of Dimensions	:	3
Number of Bodies	:	N
Coordinate System	:	Cartesian
Integration Technique	:	Variable step, fixed step (both)
Porgram Language	:	Fortran IV
Computer Now Used	:	IBM 7094
Trajectory Options	:	Flyby, rendezvous
Specific Impulse	:	Variable, constant
Power Options	:	Constant, function of time, function of distance
Other Options	:	Nonoptimal or optimal steering, computed or tabular thrust, others, see report
Input (briefly)	:	Position and velocity or Julian dates, V_∞, Isp, α
Initial Guesses Required	:	Steering angles
Parameters Optimized	:	Can optimize any selected parameter
Optimization Technique	:	Newton-Raphson (modified)
Output (briefly)	:	Time history, Isp, T/W, payload
Planetocentric Phase	:	High-thrust capture and departure
Limitations of Program	:	Optimal phasing logic not included yet
Documentation	:	User's Guide (Vol. I & II), Interim Report NAS 7-503
Availability	:	See John Driver, JPL
Other Comments	:	The program is not completely ready for general use.

Company/Organization	:	United Aircraft Research Laboratories
Name of Program	:	Mass ratio optimization (simplified & improved payload fraction definition) F487
Authors/Contact	:	R. Ragsac/Betty Knose
Program Funded by	:	Company

<u>Description</u>

Number of Dimensions	:	3
Number of Bodies	:	2
Coordinate System	:	Cartesian
Integration Technique	:	Fixed step
Program Language	:	Fortran V
Computer Now Used	:	Univac 1108
Trajectory Options	:	Rendezvous
Specific Impulse	:	Constant
Power Options	:	Constant
Input (briefly)	:	Julian dates, V_∞, α, η, thrustor specific mass curve
Initial Guesses Required	:	Isp, μ_1
Parameters Optimized	:	Isp, μ_w, $\int a^2\,dt$, coast time
Optimization Technique	:	Newton-Raphson
Output (briefly)	:	Isp, $\int a^2\,dt$, μ_w, μ_1, μ_L powered time
Planetocentric Phase	:	Not included in program
Limitations of Program	:	Travel angle, powered time is approximate
Documentation	:	Sample input and explanation
Availability	:	Yes
Other Comments	:	Differs from F530 in capability to maximize realistic definition for payload fraction

Company/Organization	:	United Aircraft Research Laboratories
Name of Program	:	High & Low Thrust Mass Optimization/F211
Authors/Contact	:	Betty Knose/R. Ragsac
Program Funded by	:	NASA Contract NAS 2-2928

Description

Number of Dimensions	:	2 or 3
Number of Bodies	:	2
Coordinate System	:	See other comments
Integration Technique	:	See other comments
Program Language	:	Fortran V
Computer Now Used	:	Univac 1108
Trajectory Options	:	Flyby, rendezvous, round trip
Specific Impulse	:	Constant
Input (briefly)	:	α, high and low-thrust propulsion parameters, table of μ_L, μ_W Isp vs. V_∞
Initial Guesses Required	:	None
Parameters Optimized	:	Mass on Earth parking orbit
Optimization Technique	:	Search
Output (briefly)	:	System masses and propulsion parameters
Planetocentric Phase	:	Hyperbolic excess speeds (high-thrust system)
Documentation	:	User's Manual
Availability	:	See NASA, MAD
Other Comments	:	Mass optimization only; trajectory data are input

Company/Organization	:	United Aircraft Research Laboratories
Name of Program	:	Mass Ratio Optimization (simplified payload fraction) F530
Authors/Contact	:	R. Ragsac/Betty Knose
Program Funded by	:	Company

Description

Number of Dimensions	:	3
Number of Bodies	:	2
Coordinate System	:	Cartesian
Integration Technique	:	Fixed step
Program Language	:	Fortran V
Computer Now Used	:	Univac 1108
Trajectory Options	:	Rendezvous
Specific Impulse	:	Constant
Power Options	:	Constant
Input (briefly)	:	Julian dates, V_∞, α
Initial Guesses Required	:	None
Parameters Optimized	:	Isp, μ_w, $\int a^2\,dt$, coast time
Optimization Technique	:	Newton-Raphson
Output (briefly)	:	Isp, $\int a^2\,dt$, μ_w, μ_L, μ_1 powered time
Planetocentric Phase	:	Not included in program
Limitations of Program	:	Travel angle ~3π, powered time is approximate
Documentation	:	Sample input and explanation
Availability	:	Yes
Other Comments	:	Optimization of Isp and μ_w uses accurate approximation technique, single coast period only

Company/Organization	:	United Aircraft Research Laboratories
Name of Program	:	Variable Power, Variable Thrust Option/F369
Authors/Contact	:	Mrs. E. Knose, Mr. G. Thrasher, UARL
Program Funded by	:	NASA Contract NAS 8-11309, NAS 2-2928

<u>Description</u>

Number of Dimensions	:	3
Number of Bodies	:	2
Coordinate System	:	Cartesian
Integration Technique	:	Fixed step
Program Language	:	Fortran IV
Computer Now Used	:	Univac 1108, Fortran V
Trajectory Options	:	Flyby, rendezvous, solar probe
Specific Impulse	:	Variable
Power Options	:	Constant, function of time, function of distance
Input (briefly)	:	Position and velocity, Julian dates, V_∞, power option input
Initial Guesses Required	:	None
Parameters Optimized	:	$\int a^2\, dt$
Optimization Technique	:	Newton-Raphson
Output (briefly)	:	Time history, $\int a^2\, dt$
Planetocentric Phase	:	Not included in program
Documentation	:	Sample input and explanation
Availability	:	Determined by NASA

Company/Organization	:	United Aircraft Research Laboratories
Name of Program	:	Constant-Thrust, Multiple-Coast/F615
Authors/Contact	:	C. P. Van Dine/Betty Knose
Program Funded by	:	NASA Contract NAS 2-2928

<u>Description</u>

Number of Dimensions	:	2 or 3
Number of Bodies	:	2
Coordinate System	:	Cartesian
Integration Technique	:	Fixed step
Program Language	:	Fortran V
Computer Now Used	:	Univac 1108
Trajectory Options	:	Flyby, rendezvous
Specific Impulse	:	Constant
Power Options	:	Constant
Other Options	:	Optimize Isp and μ_w, fix μ_w opt Isp, fix Isp opt μ_w, or input Isp and μ_w
Input (briefly)	:	Julian dates, V_∞, α, efficiency parameter
Initial Guesses Required	:	None
Parameters Optimized	:	Isp μ_w, $\int a^2\, dt$, coast time
Optimization Technique	:	Newton-Raphson
Output (briefly)	:	Time history, Isp, payload, $\int a^2\, dt$, powered times
Planetocentric Phase	:	Not included in program
Limitations of Program	:	Travel angle ~3π
Documentation	:	Programmer's Manual, UARL F-910352-13
Availability	:	See NASA, MAD
Other Comments	:	Two heliocentric coast periods allowed

National Aeronautics and Space Administration
Moffett Field, Calif., 94035, May 17, 1968
130-0604-07

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